Vector Field Visualization of Magnetospheric Dynamics

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Abstract

The 3D magnetic fields produced by magnetohydrodynamic (MHD) simulations are often very complex and difficult to analyze. Critical point analysis is an important technique utilized in vector field visualization to represent the important aspects of the vector field topology. We apply critical point analysis to 3D magnetic fields, enabling space physicists to visualize the complex nature of magnetospheric dynamics for the first time on a global scale.

Keywords: critical point analysis, vector field visualization, magnetospheric dynamics

Introduction

The magnetosphere of the Earth constitutes one of the most important elements of the Sun-Earth linked system. Therefore, it plays a major role in the formation and transmission of space weather relevant phenomena. Visualizing the complex nature of the magnetospheric dynamics is an important aspect of space weather analysis, which has to a large degree eluded space physicists. An important aspect of this analysis is the 3D topology of the Earth's magnetic field and the location of magnetic reconnection. Theoretically, reconnection has been studied in two dimensions but is harder to study in three dimensions. To fully understand the role of reconnection in the Earth's magnetosphere especially when symmetry is broken, it is important to analyze the 3D topology. We have found critical point analysis to be a valuable tool for finding these reconnection points. The Community Coordinated Modeling Center (CCMC) [1] is developing a 3D visualization tool called Space Weather Explorer (SWX) [2] to aid space science researchers in understanding their simulation data.

Currently SWX displays output from the Block Adaptive Tree Solar-wind Roe Upwind Scheme (BATS-R-US), the first model selected for study by the Community Coordinated Modeling Center (CCMC). BATS-R-US is a 3D magnetohydrodynamics (MHD) code developed at the University of Michigan for massively parallel computers using adaptive mesh refinement (AMR) [3]. AMR has become an increasingly popular technique used in a variety of fields such as computational physics, computational fluid dynamics, and cosmology. Within the last couple of years, the visualization community has only just begun to develop techniques to directly visualize AMR data [4, 5, 6]. The output from BATS-R-US is converted to HDF5 [7] using a format similar to ChomboVis [4]. SWX uses OpenDX [8] for visualization. OpenDX does not directly support AMR data; therefore, the critical point analysis and streamline calculations are accomplished by C++ code that is called from SWX.

Critical Point Analysis

Critical point analysis is an important technique utilized in vector field visualization [9, 10, 11, 12]. Critical points (referred to as neutral points by plasma researchers) are points at which the magnitude of the vector field vanishes. These points can be used to accurately represent the important aspects of the vector field topology. We apply critical point analysis to 3D magnetospheric magnetic fields produced by BATS-R-US. Parnell et al. [13] provides the physical theoretical structure of 3D magnetic neutral points. We recently learned that Cai et al. [14] have also successfully applied critical point analysis to visualize the earth's magnetotail topology; however, their data sets are obtained from 3D full electromagnetic particle simulations.

Critical points are identified by a straightforward extension of the approached used by the TOPO module of the Flow Analysis Toolkit (FAST) [9] to AMR data. We have found that critical points are often located very near one another, contributing to visual clutter commonly encountered in vector field visualization. Therefore, the minimum resolution of the block in which a critical point resides is determined. All critical points within a factor of this minimum resolution (we use 1.5) are merged into a single critical point.

Each critical point is then classified based on the eigenvalues of its Jacobian matrix using modified portions of code from the TOPO module of FAST. Finally, seed locations for streamline integration are determined based on the classification of the critical point and the eigenvectors of its Jacobian matrix. Using an approach similar to Vivek et al. [11], the number of seeds and the distance between them is based on the distance between the critical point and the nearest other critical point. Thus, critical points which are clumped near one another will not have as many seeds as those which spaced further apart. Streamlines are integrated using the adaptive fourth order Runge-Kutta-Cash-Karp method [15]. Streamlines are piped to SWX in the OpenDX native format for visualization.

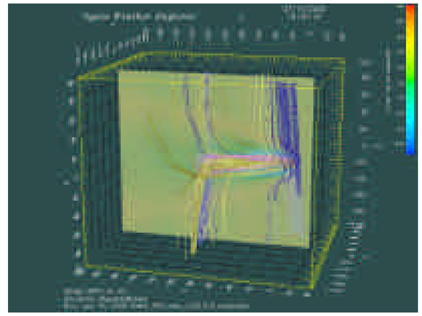

Figure 1. Space Weather View (SWX). Critical point analysis reveals the complex nature of magnetic reconnection.

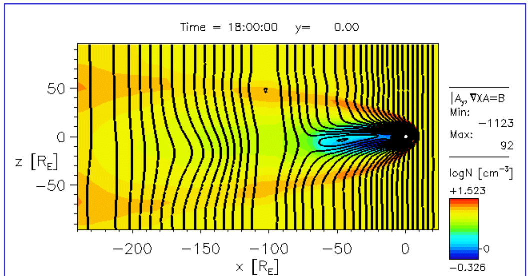

Figure 2. CCMC Web Interface. BATS-R-US, July 15, 2000.

Results

Figure 1 illustrates the results of using critical point analysis to visualize the magnetic field from a BATS-R-US simulation of the July 15, 2000 space weather event, which was using data from the Geotail-MGF instrument as input. The magnetic field lines are represented by blue (interplanetary), magenta (closed), and yellow (open) tubes. The loop-like magnetic field lines (yellow) indicate the position of the core of the ejected plasmoid. Critical point analysis in conjunction with the animation features of SWX allows physicists to locate the plasmoids and follow the evolution of the plasmoids during the simulation. Complicated magnetic field singularity can be clearly identified at the near earth reconnection site.

The same data set used for Figure 1 is used by the CCMC Web Interface to plot Figure 2. Notice that reconnection is evident in both figures; however, the three dimensional nature of plasmoid formation is not seen in Figure 2. Figure 1 indicates the earth's magnetail has been extended much further than Figure 2 suggests. This is most likely due to the two dimensional stream line tracing used by the CCMC Web interface.

Conclusions and Future Work

Critical point analysis accurately locates the near-Earth reconnection site; thus, physicists are able to study the dynamics around the near-earth reconnection site. This capability provides a new and critical tool for the understanding of substorm dynamics and other space weather applications. Critical point analysis also enables studies of reconnection points at the boundary between the magnetosphere and the magnetic field of the solar wind. The location of these reconnection points is dependent on the direction of the magnetic field of the solar wind. Next we plan on extending critical point analysis to the magnetic fields produced by the UCLA Geospace General Circulation Model (GGCM) global 3D MHD code [16]. Thus, CCMC scientists will be provided with a unique, new tool for the comparison of magnetospheric dynamic behavior, as modeled by the BATS-R-US and UCLA-GGCM MHD codes.

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